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The Role of Working Memory

in Language Comprehension

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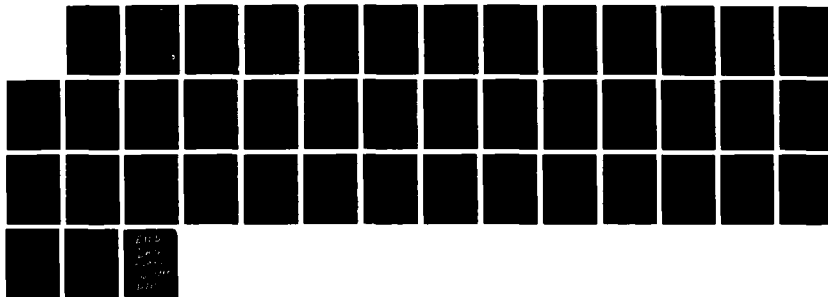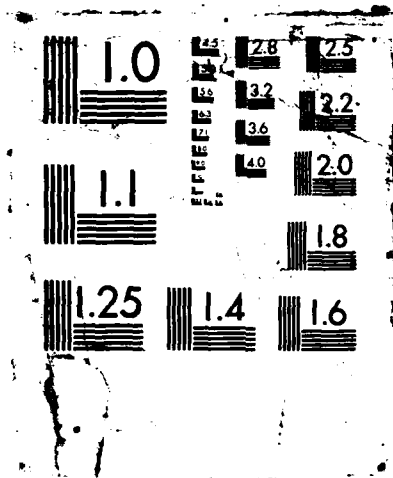
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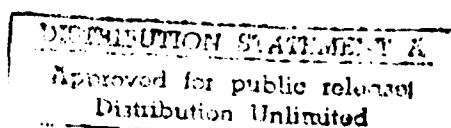Marcel Adam Just

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This chapter provides an account of the transient computational and storage demands that typically arise during comprehension, and of the information management policies that attempt to satisfy those demands. The chapter describes a number of recent studies that examine the trading relation between computation and storage in working memory during language comprehension. Comprehension processes tends to minimize storage requirements by minimizing the number of partial products that have to be stored. The minimization is accomplished by immediately digesting as much of the information from the text as possible (what we have called the immediacy of processing). rather than using a "wait-and-see" strategy.

A second focus is on the differences among individuals in their ability to maintain information in working memory during comprehension. We have found that such individual differences in working memory capacity are closely related to large and stable individual differences in reading comprehension ability.

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Much of what we think about flies past our consciousness, usually without us being aware of it. William James said "The mass of our thinking vanishes for ever, beyond hope of recovery, and psychology only gathers up a few of the crumbs that fall from the feast" (p.276). This chapter deals with the site of that feast, namely, working memory. Even though the feast seemed inaccessible to James, recent studies of eye-fixations during complex thinking have begun to reveal some of the richness of the feast. These studies have revealed that considerable computation occurs during the ten seconds that it takes to solve a simple analogy problem or during the four seconds that it takes to understand a sentence. The richness of the intermediate computations is evident in empirical measures of performance, as well as in the computer models that simulate the psychological processes. Computer simulation models of cognition have had to come to grips with the intermediate products of thought in order to generate the final products. Thus, simulation models have been forced to provide a tentative characterization of the organization of these computations in working memory.

Working memory plays a central role in all forms of complex thinking, such as reasoning, problem solving, and language comprehension. However, its necessity in language comprehension is especially evident. Because language processing must deal with a sequence of symbols that is produced and perceived over time, the temporary storage of information is an inherent part of comprehension. Working memory plays a central role in storing the partial and final products of our computations as we process a stream of words in a text, allowing us to mentally paste together ideas that are mentioned separately in the text or are only implied. This chapter examines how people comprehend language while simultaneously storing relevant information from the text. This focus treats working memory as a workspace that is used during comprehension and brings to light the purpose of working memory in the human processing architecture.

For the past 100 years, theories and research on working memory (or short-term memory, as it used to be called) have focused on the storage of information for retrieval after a brief interval. A familiar example used to illustrate the purpose of short-term memory is the storage of a telephone number between the time when it is looked up in a phone directory and the time when it is dialed. Short-term memory was typically conceptualized as a storage device, permitting a person to simply hold "items" until they were recalled. It was conceptualized and investigated in the context of retrieval, rather than in the context of performing a cognitive task such as reasoning, language understanding, or mental arithmetic. Another, related, function attributed to short-term memory is its role as a stepping-stone on the path to long-term memory. In this view, short-term memory is the place where information is held while it is being memorized. Memorization might consist of rehearsal or some sort of elaboration, such as forming associations, chunks, or images. The studies of memorization and learning revealed a number of regularities concerning the capacity and nature of short-term memory. However, such studies had little to say about the role of short-term memory in other forms of cognition that are more computationally intensive. In any case, intentional memorization seldom occurs outside laboratories or formal study situations, so it is unlikely to have been the major purpose of short-term memory.

Then why did Mother Nature give us working memories, if we do not typically have to memorize unrelated items for either short or long periods of time? We argue that the

major purpose of working memory is to provide temporary storage during thinking. such as the type of thinking that constitutes problem solving. planning. and language production and comprehension. In these tasks. the information that a person produces. or perceives. or uses is distributed over time. For example. in syllogistic reasoning. the premises are encountered one at a time and one of the major bottlenecks in the reasoning is in appropriately integrating the successive premises. In such tasks. successful performance requires actively considering more than one idea at a time. The activated elements that participate in the current stream of thought constitute working memory. These activated elements are the partial and final products of thought. They can originate from a perceptual encoding of an event in the outside world. or they can be a product of mental symbol manipulation. Thus. working memory is a computational arena or workspace. a proposal first made by Newell and Simon (1972).

An extreme view might hold that the driving force behind the evolution of working memory was the desirability of processing the seriality of speech. and that other forms of serial thinking evolved as a result of the increased working memory capacity. It could be that language first evolved in those members of the species who happened to have larger working memory capacities than the norm. because they could accommodate the sequences of distinguishable sounds (symbols) that the evolving articulatory system could produce. The adaptiveness of a larger working memory for holding the sequence in mind may have encouraged its continuing evolution. As a result of the larger working memory adapted to language. many other complex forms of thinking could have become possible. such as planning and problem-solving. This proposal can also be stated in a much less extreme form. namely that working memory evolved in conjunction with the unrelenting seriality of all kinds of mental and physical events. including language. At any rate. the mental processes in reading comprehension can provide a window through which to examine the role of working memory in language comprehension.

The functioning of working memory in language comprehension brings into relief a different set of properties than those highlighted by tasks that involve little computation or that stress retrieval. It is in working memory that a reader stores the theme of the text he is reading. the representation of the situation to which it refers. the major propositions from preceding sentences. as well as a running. multi-level representation of the sentence he is currently reading. The storage and computational demands imposed by the reading of a text fluctuate from moment to moment. as a text introduces long-distance dependencies. digressions. or particularly demanding computations. In this regard. the management of information that occurs during comprehension may be paradigmatic of complex thinking. both of the linguistic and non-linguistic type.

This chapter focuses on two aspects of working memory and comprehension. One focus of the chapter is on the transient computational and storage demands that typically arise during comprehension. and on the information management policies that attempt to satisfy those demands. We will show how the component processes of comprehension operate within the constraints imposed by the limitations of working memory resources. The organization of the comprehension processes tends to minimize storage requirements by minimizing the number of partial products that have to be stored. The minimization is accomplished by immediately digesting as much of the information from the text as possible (what we have called the immediacy of processing). rather than using a "wait-and-see" strategy.

A second focus is on the differences among individuals in their ability to maintain information in working memory during comprehension. We have found that such individual

differences in working memory capacity are closely related to large and stable individual differences in reading comprehension ability.

The paper is organized into two main sections. which share both of these foci. In the first section. we will present an overview of the role of working memory in comprehension from the computational framework of production systems. In the second part. we will describe a number of recent studies that examine the trading relation between computation and storage in working memory during language comprehension. Although we will analyze working memory in the context of language comprehension. we believe that this particular view reveals general properties of working memory.

Working memory from a computational viewpoint

The main function of working memory is transient storage of partial results in the service of computation. This assumption underlies all computer simulation models of human thought that are cast as production systems. and it underlies our view of the human processing of language. The transient storage includes inputs. partial products. and final products to support the continuous flow of symbol manipulation in working memory. The distinction between partial and final products is not always sharp. because the information that is the final product of one computation may be the input or the partial product of another computation. The main function of working memory is not simply storage of inputs for subsequent retrieval.

When working memory is viewed as a computational arena. it becomes clear that its capacity should be construed not just as a storage capacity (perhaps measured in chunks). but as operational capacity. or throughput. By analogy. consider how the capacity of a hospital to perform surgery might be measured. Typically. we are interested in some measure of throughput. such as the number of surgical procedures of a given type that can be performed per day. rather than in a static measure. such as the number of surgical theatres. Of course. the surgical capacity of a hospital depends on what types of procedures are involved. what instrumentation is available. the skill of the surgeons and support personnel. and so on. So operational capacity must be specified in terms of the number of procedures of a given type per unit time. such as the number of appendectomies that can be performed per day. Similarly. any measure of working memory's operational capacity must take into account the nature of the information being processed and the nature of the operations that are being applied.

Computational assumptions of the production system approach. The nature of working memory is highlighted by computational models that provide a characterization of the intermediate products of comprehension. To illustrate how this approach characterizes working memory. we will briefly describe the computational model of comprehension we have used. which is called READER. READER was designed to simulate a college student reading a short scientific text in order to summarize it. READER takes in the text from left to right. constructing the linguistic and referential representation as it goes. The time that READER spends on various parts of the text is proportional to the time that human readers spend. and the final recall or summary is similar to the ones generated by students. READER is a production system model derived from a family of production systems designed by Allen Newell and his colleagues (Forgy & McDermott. 1977: Newell. 1967: Newell & Simon. 1972): consequently. many of the observations we make about the role of working memory in READER will generalize to most other production systems.

Production systems are a particular kind of information processing organization first advanced as a model of human thought by Newell and Simon (1972). In this type of model, procedural knowledge consists of a set of autonomous units called productions. Each production consists of a condition-action contingency that specifies what mental action is to be taken when a given information condition arises in working memory. Typically, the mental action of a production changes the contents of working memory, thereby enabling another production. For example, encoding the word *the* might enable a production that would add to working memory the knowledge that a noun phrase has been encountered. The knowledge that a noun phrase has been encountered might in turn enable another production that relates the new noun phrase to the rest of the syntactic structure of the sentence being read. All production systems share this basic organization, although there exist interesting variations on the main theme (cf. Klahr, Langley, & Neches, 1987).

READER deviates in many important ways from conventional production systems. First, conventional production systems allow only one production to execute its actions on a given cycle; by contrast, READER allows all the productions whose conditions are satisfied to fire in parallel. Second, in conventional systems, elements are either present or absent from working memory; by contrast, in READER, elements can have varying degrees of activation. Thus the condition of a READER production specifies not just the presence of an element, but the minimum activation level (i.e. the threshold) at which the element satisfies the condition. Third, in conventional production systems, the productions create or delete elements in working memory. In READER, productions may also change the activation levels of elements by propagating activation from a condition element to an action element.

In the READER model, working memory consists of propositions whose activation levels are above a fixed threshold. Working memory elements can in effect be pointers to structures in long-term memory or they can be symbols that have been newly encoded or constructed during the process of thinking. The activation levels of the propositions affect their availability for various computations. Forgetting of a proposition from working memory occurs when its activation level falls belows the threshold. In the next section, we will describe the relevance of these properties to the role of working memory in comprehension. A more detailed description of both the READER model and its production system environment (CAPS, for Concurrent, Activation-based Production System) can be found elsewhere (Just & Carpenter, 1987: Just & Thibadeau, 1984: Thibadeau, Just, & Carpenter, 1982).

The same productions can fire reiteratively, over successive cycles, such that the activation levels of the output elements are successively incremented (or decremented) until they reach some threshold. Thus the symbolic manipulations occur not just as a one-shot firing, but a repeated action with cumulative effects. This regimen resembles that of a neural network, in which one unit can repeatedly activate or inhibit another. However, unlike some neural networks, CAPS permits dynamic connections between units (created by the relation between the condition and the action of a production). Also, the units can be pointers to arbitrarily large structures. Thus the flow of processing is under conventional production system control, but the nature of the processing consists to a large degree of propagation and accumulation of activation through a dynamically constructed network.

In the course of READER's processing of a text, its working memory accumulates information at several different levels of representation, such as the lexical, syntactic, and referential levels. Within a given level of representation, working memory provides the storage of elements whose onsets are separated in time but which must be processed as co-

arguments of some operation, such as a syntactic operation that relates the first word of a clause to the last word. Moreover, the multi-level representation of language in working memory provides a centralized repository in which information developed at one level of analysis (like the syntactic level) is available for potentially influencing another level (like the lexical level). This latter function is sometimes referred to as a blackboard model (Reddy, 1980), in which the metaphor for working memory is a shared blackboard on which different types of processes write their partial and final results and make them available to other processes.

Capacity. One of the attractions of production systems for modeling human thought is the potential correspondence between its working memory and human short-term memory, as Newell and Simon (1972) pointed out. In most production system models that attempt to simulate human thought, including the READER model, the number of elements is very large, on the order of many tens of elements, and in some cases, hundreds of elements. In addition, each element can contain arbitrarily deep embeddings. In those production system models that make no pretense of cognitive simulation, the number of elements in working memory sometimes rises even higher, up to thousands of elements. To be sure, some of these large numbers occur because the modeler doesn't bother to clean up unneeded elements from working memory, and doesn't want to bother with the implementation of a forgetting mechanism, let alone a psychologically plausible forgetting mechanism. But even if unneeded elements were deleted from the working memory of existing models, the remaining number of elements would still be large. At least a few tens of elements in an activated state are needed to allow the computations to proceed. Contemporary cognitive simulation models typically attempt to describe a complex thought process that requires an orchestrated sequence of many computations. This kind of processing focuses on the necessity for storing many intermediate products and control information in working memory. Those few production system simulations whose knowledge elements have activation levels can make provision for decay of information from working memory by means of decrementing the elements' activation levels (e.g. Anderson, 1983). In general, however, computational models seldom take account of the type of capacity limitation of short-term memory described by Miller (1956) and incorporated into subsequent models of short-term memory (Atkinson & Shiffrin, 1968).

To illustrate the point in the case of language comprehension, consider the abbreviated description of the contents of READER's working memory (shown in Table 1) just after it has processed the simple four-word sentence *Flywheels are mechanical devices.* The claim is that as a person reads and understands a complex sentence, there are many more than seven elements in working memory. Although the representation shown in Table 1 can be recast in many different ways, and the psychological reality of the propositions presented there cannot always be defended, both the numerosity of elements and the multiplicity of levels of representation would probably not change drastically under a different representation. Moreover, the numerosity of elements and multiplicity of levels probably characterize other forms of complex thought as well, such as problem-solving and spatial thinking.

The READER model illustrates the fact that many elements must be activated during comprehension. However, the model does not provide an account of the constraints on working memory, except for the following. The slots that hold the words of a sentence are re-used for each successive sentence, so that the exact wording of a sentence is forgotten as the next sentence is read. This constraint on the storage of lexical information accounts for some of the human forgetting of exact wording that is discussed later in the chapter. An adequate model of the role of working memory in comprehension should specify the

constraints that apply to all levels of comprehension.

TABLE   1 - TRACE of READER's working memory for a simple 4-word sentence

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Although complex thought requires transient storage of many symbols. there nevertheless do exist real limitations on our working memories.   We have only to try some mental arithmetic (768 x 536 = ?) to experience the frustration caused by such limitations. The capacity limitations in short-term memory have been repeatedly demonstrated experimentally and characterized as a limit of approximately seven chunks (as first proposed by Miller. 1956. in his classic paper on the capacity of short-term memory).   The theoretical problem raised by these limitations is to explain how people can reason. understand language. or solve problems in spite of these capacity limitations.   A theory of working memory must describe the information management strategies (such as immediacy of comprehension. described below) and the resource allocation policies that are invoked when the demand for working memory resources outstrips the supply.

Conventional theories of short-term memory and theories of working memory differ not only in the capacities they attribute to the memory. but also in the stuff that is being stored. In a working memory. what is stored is not seven or five items. but a set of pointers that index relational data-structures. The relational structures can be quite large in some circumstances. and can be a part of long-term memory.   In the course of performing some intellectual task. working memory holds *related* information that is sometimes configured as a network.   The relatedness can be the result of prior association in long-term memory or the result of an integration performed by the ongoing computations.   By contrast. short-term memory theories often focused on the storage of items that were unrelated to each other.   Storing unrelated items is not the main purpose of working memory. although people occasionally do this sort of task. when they try to store a phone number or a short grocery list.   Even then. they try to construct relations to help them remember the items.   However. most of the time working memory stores the stuff of ongoing thought. which is generally a collection of interrelated concepts.

The need for storage during comprehension.   Because language is a sequential communication channel. a reader or listener has to temporarily store early parts of the sequence in order to relate them to later parts.   Consider the information a reader needs to process the following sentence:

> *A familiar example used to illustrate the function of short-term memory is the storage of a telephone number between the time when it is looked up in a phone directory and the time when it is dialed.*

At the point of processing the phrase *is the storage.* the reader must keep in mind the noun phrase nine words earlier that serves as the sentence subject (*a familiar example*). as well as information in the relative clause: the final pronoun (*it*) must be related to a referent that occurred 17 words earlier.   As this example illustrates. ordinary prose. and particularly academic prose. imposes considerable storage demands.   The demands can be increased further by interruptions. digressions. or long-distance dependencies.   Furthermore. experimenters can add extraneous processing burdens by imposing additional demands. by requiring the reader to store some portions of the text verbatim. or to store some extraneous information. or to perform some additional task during comprehension.

Table 1 Some of the propositions that constitute the representation of the sentence: *Flywheels are mechanical devices*

Proposition	Processing Level
(WORD-1 :IS *flywheels*)	
(WORD-1 :HAS *CONCEPT-1*)	lexical
(*CONCEPT-1* :HAS REFERENT-1)	referential
(REFERENT-1 :IS FLYWHEEL-1)	
(WORD-2 :IS *are*)	
(WORD-2 :HAS *CONCEPT-2*)	lexical
(WORD-2 :HAS SUBJECT-2)	syntactic
(SUBJECT-2 :IS WORD-1)	
(*CONCEPT-2* :IS CATEGORY-MEMBERSHIP-1)	
(CATEGORY-MEMBERSHIP-1 :HAS SEMANTIC-SUBJECT-1)	semantic
(SEMANTIC-SUBJECT-1 :IS FLYWHEEL-1)	
(WORD-3 :IS *mechanical*)	
(WORD-3 :HAS ADJECTIVE'S-NOMINAL-3)	syntactic
(ADJECTIVE'S-NOMINAL-3 :IS WORD-4)	
(WORD-4 :IS *devices*)	
(WORD-4 :HAS *CONCEPT-4*)	lexical
(WORD-4 :IS OBJECT-2)	
(OBJECT-2 :HAS VERB-2)	syntactic
(VERB-2 :IS WORD-2)	
(WORD-4 :HAS REFERENT-4)	referential
(REFERENT-4 :IS DEVICES-1)	
(CATEGORY-MEMBERSHIP-1 :HAS SEMANTIC-OBJECT-1)	semantic
(SEMANTIC-OBJECT-1 :IS DEVICES-1)	

Source: Adapted from Thibadeau, Just, & Carpenter, 1982, Table 4, p. 173.

This list of naturally occurring and laboratory events that can increase the need for storage during comprehension illustrates several points. The storage demands vary in the amount and kind of resources they require. they are imposed by a variety of sources. and they fluctuate from moment to moment. A theory of working memory must account for the way people rise to the challenge of such demands. or for the resulting difficulties when they fail to do so.

Immediacy of Interpretation

The way that comprehenders deal with the sequential nature of language is to try to interpret each successive word of a text as soon as they encounter it. and integrate the new information with what they already know about the text and its subject matter. We have referred to this processing strategy as the *immediacy of interpretation*. A reader tries to digest each piece of the text as he encounters it (Just & Carpenter. 1980. 1987). The immediacy of interpretation entails many levels of comprehension: encoding the word. accessing its meaning. associating it with its referent. and determining its semantic and syntactic status in the sentence and the discourse. It is important to note that although the attempt at interpretation is immediate. the text can force postponement by withholding essential information. In such cases. the postponement is out of necessity rather than strategic choice. The default strategy is to interpret immediately.

The relation between immediate interpretation and working memory capacity is straightforward. Immediate interpretation minimizes the storage of unanalyzed portions of text. The interpretive computations are applied as soon as the inputs are available. Low-level inputs (such as the shapes of individual words or phrases) generally do not have to be stored as a sequence of unrelated items while subsequent words and phrases are read. Instead. what is stored is the interpreted representation.

The immediacy of interpretation can be contrasted with a different strategy for dealing with the sequential nature of language. namely a wait-and-see strategy. A reader can always increase the probability of correctly interpreting a given word or phrase if she postpones interpreting it until she sees what follows in the sentence. Wait-and-see strategies have been proposed by several researchers (Kimball. 1973: Marcus. 1980) Comprehenders using the immediacy strategy still use the context that follows a piece of text to help interpret that piece. but they do so by elaborating or amending an already existing interpretation. rather than waiting for the context before making any interpretation.

The clearest evidence for the immediacy strategy is that the time spent looking at a word is strongly influenced by the characteristics of that word (e.g.. Just & Carpenter. 1980: Carpenter & Just. 1983). The gaze duration on a word is directly related to the word's length (measured in number of letters). an effect we attribute to the encoding of the visual form of the word. Thus each word is encoded while it is being fixated. The gaze duration on a word is also related to the word's normative frequency in the language. an effect we attribute to the process of accessing the word's meaning in the mental lexicon (Just & Carpenter. 1987). Readers spend longer on a rare word like *sable* than on a common word like *table*. Thus the meaning of each word is being accessed while the word is being fixated. The downward slopes of the lines in Figure 1 indicate the decrease in gaze duration with the logarithm of the word's frequency. Each of the lines in the figure corresponds to words of a particular length. and progression of lines (from bottom to top) indicates the increase in gaze duration with word length. independent of frequency.

Figure 1 relating gaze duration to word length and frequency

Unusually long gaze durations can also be produced by words that present a difficulty because of their role in the syntax or semantics of a sentence. For example, a reader will pause longer on a semantically anomalous word compared to an appropriate word of comparable length and frequency: a reader will also pause longer on a word that requires a complex syntactic computation. compared to one that is syntactically less complex. These kinds of results indicate that the semantic and syntactic analyses of each word must be occurring while the word is being fixated. Thus the evidence indicates immediacy at several levels of interpretation. such as the lexical (Just & Carpenter, 1980: Just & Carpenter, 1983), syntactic (McDonald & Carpenter, 1981), and text levels (Dee-Lucas, Just, Carpenter, & Daneman, 1982). If a word introduces an increase in the processing load at any of these levels. there is an increased gaze duration on that word. All these results constitute strong support for the immediacy of interpretation. Thus the varying processing burden imposed by the successive words of a text is borne as soon as it is encountered. We will show that this fluctuating computational burden draws on some of the same resources as the transient storage of information in working memory.

Why immediacy works. There are two aspects of language use that minimize the costs and maximize the benefits of immediacy. The costs (such as making an incorrect interpretation) are low because it generally *is* possible to compute the correct interpretation of a word when it is first encountered. Wait-and-see proponents focus on contrived sentences presented without context. in which a reader has so little knowledge that he has no choice but to wait-and-see. However, normal context and normal sentences make it possible for the reader to develop strategies that succeed on an overwhelming proportion of the sentences people normally process. Readers use their knowledge of the context and their knowledge of relative frequencies of alternative interpretations in choosing the most likely interpretation. The benefit of immediacy is that it reduces the memory load of retaining information in an unprocessed form while waiting-and-seeing.

Trade-offs among processes in working memory

In the production system model of comprehension. working memory is the site at which productions collaborate and compete in calculating the intermediate and final products of comprehension. Although productions at many levels may be simultaneously involved in processing. there are some capacity limitations. Readers are usually not conscious of such limitations during normal comprehension. However. it is possible to construct a more demanding task. one in which comprehension processes must compete with other processes for working memory resources. Baddeley and Hitch (1974) proposed that working memory was both a computational and a storage arena. They devised a number of tasks that indicated that the storage and processing capabilities of working memory tended to trade-off against each other. such that a large demand on one function would degrade performance on the other.

One such comprehension task was designed to require the reader to maintain an additional set of unrelated words in working memory while reading (Daneman & Carpenter, 1980). Readers normally maintain a great deal of information in an activated form while
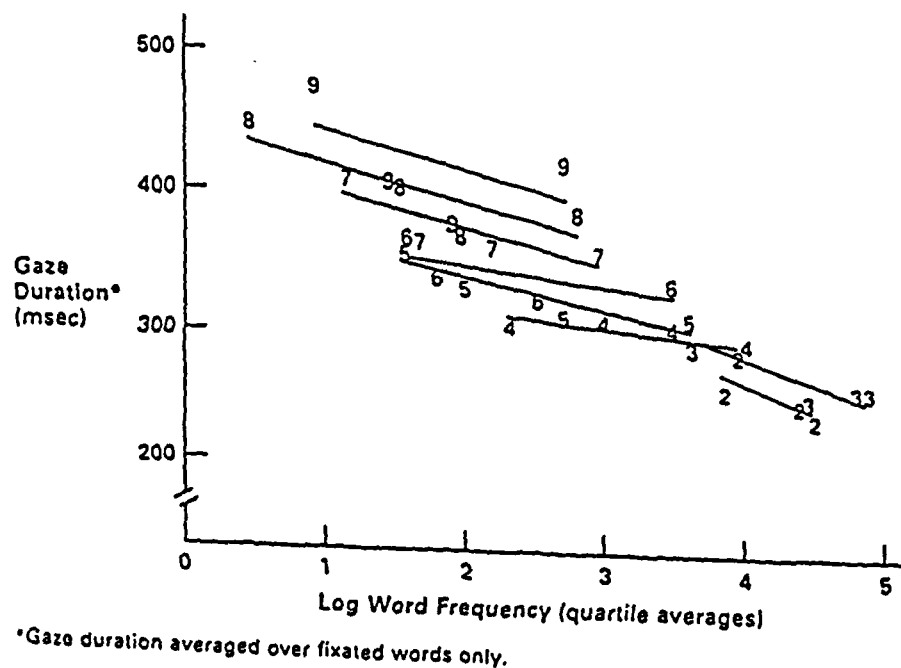
Figure 1. The average time a reader spends looking at a word (in milliseconds), as a function of the logarithm of the word's frequency. More frequent words (those with a larger log frequency) are looked at for less time than less frequent words. The eight lines represent words of different lengths--words that are two letters long, three letters long, up to nine letters long. Each point represents the mean of a quartile of the words of that length. Word frequency has an effect on words of each length. Source: Carpenter & Just, 1983. Figure 17.2, p. 288. Used with permission of Academic Press.

reading. However, the information that is activated during reading is maintained by virtue of its participation in the comprehension process. (In terms of the READER model. information is maintained by being acted upon by productions.) By contrast. maintaining even a small number of words in working memory that are extraneous to the text constitutes a considerable burden because their maintenance is not a natural outcome of normal processing. Rather. the subject must devise some extrinsic way of maintaining the items. such as rehearsing them.

Much of our research on the role of working memory in comprehension makes use of the reading span task developed by Daneman and Carpenter (1980). The task requires subjects to read a set of unrelated sentences and. at the end of the set. recall the final word of each sentence. For example. consider the following set of two sentences:

When at last his eyes opened. there was no gleam of triumph. no shade of anger.

The taxi turned up Michigan Avenue where they had a clear view of the lake.

After reading these two sentences. the subject was to recall the words *anger* and *lake*. Each subject was presented with sets containing from two to seven sentences. to determine the largest set size from which he could reliably recall all of the sentence-final words. The largest such set size was defined as his reading span. The rationale behind the test was that the comprehension processes used in reading the sentences would consume less of the working memory resources of the better readers. This would leave the better readers with more capacity to store the sentence-final words.

This task has two important virtues. One virtue is that it measures performance when both the processing and storage capabilities of working memory are being used simultaneously. The second virtue is that the reading span assessed by this procedure provides an excellent index of an individual's reading comprehension ability. and consequently is a useful psychometric instrument. By contrast. measures of passive short-term memory span. such as the ability to recall a list of digits or unrelated words. are not significantly correlated with reading comprehension performance.

The initial study demonstrated that skilled readers have greater working memory capacity in reading than less skilled readers (Daneman & Carpenter. 1980). The greater capacity for computing and storing information may arise from a variety of sources. rather than a single one. For a good reader. many processes may be both faster and more automatic. including encoding. lexical access. semantic and syntactic analysis. Working memory capacity is a property of the processing system that is the aggregate of several factors that could contribute to the individual differences in reading.

The reading spans of college students. which ranged from 2 to 5.5. were highly correlated with their reading comprehension test scores. with these correlations lying between 0.5 and 0.6 in various experiments. The correlation with reading span was even higher when specific comprehension abilities were considered individually. For example. the ability to answer a factual question about a passage was correlated between 0.7 and 0.9 with reading span in various studies. The correlation between conventional digit-span or word-span tests and reading comprehension was considerably lower. as it usually is.

A large working memory capacity could facilitate particular facets of reading comprehension. such as interrelating facts that are referred to in separate sentences.

Having a large working memory capacity would permit a reader to store a greater number of recently processed propositions in an activated state. This would be an advantage whenever there was a need to relate a newly read proposition to another one earlier in the passage. To examine this hypothesis. college students read passages like the one below. Some of the passages contained a pronoun that had to be related to a referent that had been mentioned some number of sentences previously. The experiment manipulated the number of sentences that intervened between the mention of the referent and the pronoun.

> *Sitting with Richie. Archie. Walter and the rest of my gang in the Grill yesterday. I began to feel uneasy. Robbie had put a dime in the juke box. It was blaring one of the latest "Rock and Roll" favorites. I was studying. in horror. the reactions of my friends to the music. I was especially perturbed by the expression on my best friend's face. Wayne looked intense and was pounding the table furiously to the beat. Now. I like most of the things other teenager boys like. I like girls with soft blonde hair. girls with dark curly hair. in fact all girls. I like milkshakes. football games and beach parties. I like denim jeans. fancy T-shirts and sneakers. It is not that I dislike rock music but I think it is supposed to be fun and not taken too seriously. And here he was. "all shook up" and serious over the crazy music.*

After reading the passage. the subjects were given comprehension questions. such as:

(1) *Who was "all shook up" and serious over the music?*
(2) *Where was the gang sitting?*
(3) *Who put money in the juke box?*

Readers with larger reading spans were more accurate particularly at answering questions like (1) that interrogated the identity of a person referred to by a pronoun. That is. they were better at assigning the pronoun (such as the *he* in *And here he was. all shook up*) to the referent mentioned several sentences previously in the text (*Wayne looked intense and was pounding the table...*). More importantly. the maximal distance across which a reader correctly assigned the pronoun was closely related to his reading span. as shown in Figure 2. Relating a pronoun to its referent is one type of integration process used in constructing a referential representation of the text. Readers with larger reading spans were better able to keep track of referential information. More generally. the conglomeration of processes that produces the larger reading span also produces a larger working memory capacity that facilitates reading comprehension.

Figure 2 relating span to prob. of correct pronoun assignment

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Reading in the span task

Because the reading span test provides such a good index of reading ability. it is worthwhile to directly examine the reading behavior in the test itself. and characterize the differences between subjects who are able to recall many words. typically four or five. and those who recall very few. typically two words. In particular. the eye fixation behavior has the potential of revealing which component processes of comprehension. such as word encoding or lexical access. distinguish among readers of differing spans and. by inference.
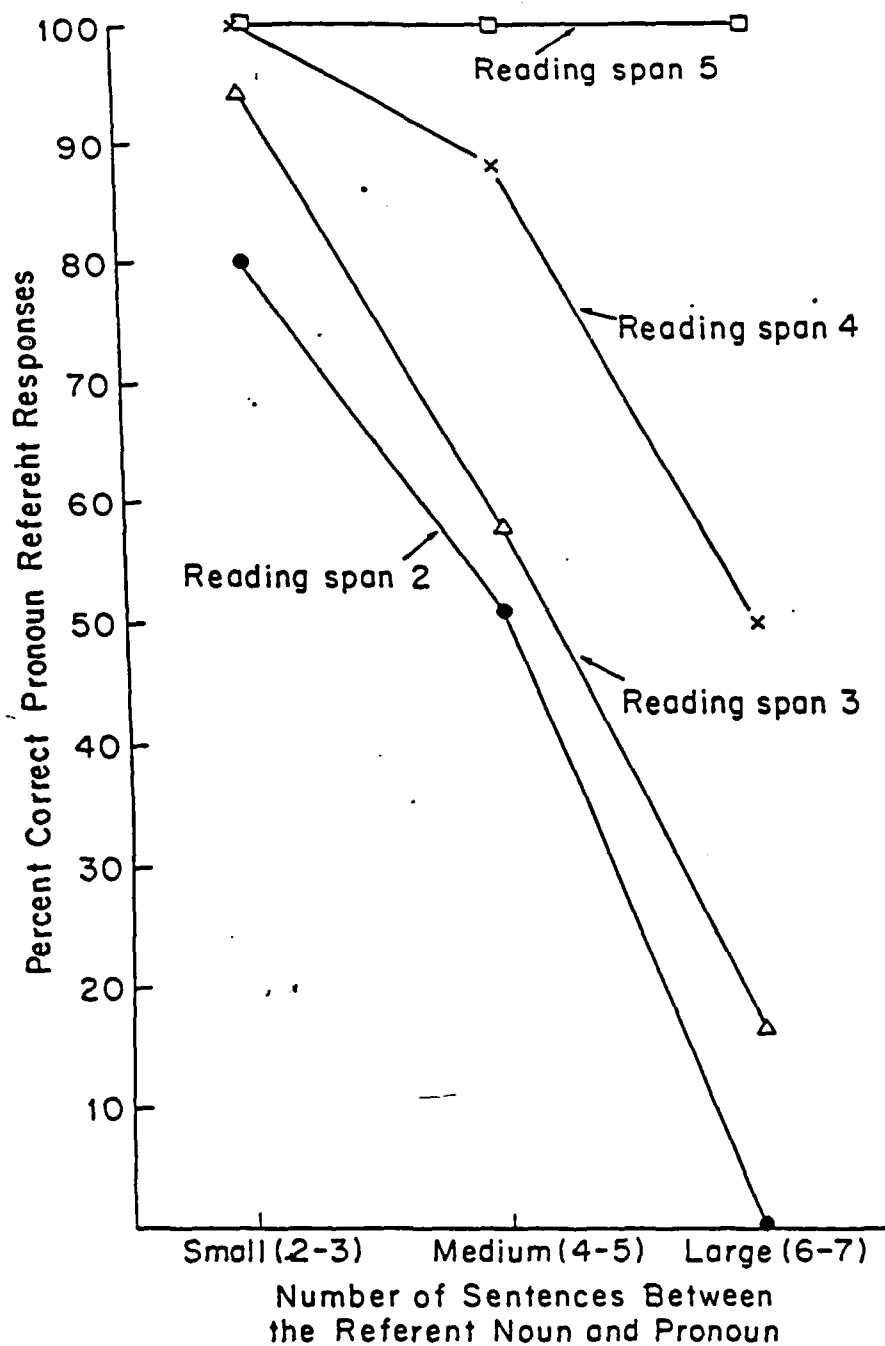
Figure 2. Readers with higher spans are more likely to correctly retrieve the pronoun's referent over a larger distance than readers with lower spans. The graph shows the percentage of correct responses as a function of the number of sentences intervening between a pronoun and its referent as a function of reading span. Source: Daneman & Carpenter, 1980. Figure 1. p.456. Used with permission of Academic Press.

differing levels of reading skill.

The procedure was similar to the usual administration of the span test. The subjects read a set of sentences aloud and tried to recall the final word of each sentence. To prevent the subjects from looking back at previously-read sentences, the lines of display that he already read were removed from the display as he progressed down the screen. The number of sentences within a set varied from 2 to 7. A subject's span was the longest set in which he correctly recalled all the sentence-final words on at least 50% of the trials. The reading spans obtained in this study were 2, 3, or 4, with a mean of 2.9. Most of the analyses focus on the contrast between six low-span (2) and six high-span (4) subjects. The methodology involved intensive testing of these subjects, producing over 6,500 gaze durations.

Eye fixations in the span task. The general description of the eye fixation behavior was that the subjects read each sentence normally until they reached the last word of the sentence, at which time they tried to memorize that word. People with high spans read the sentences faster. The mean gaze duration on each word was 278 msec for the high-span subjects, and 355 msec for the low-span subjects. This result excludes the time on the final words in the sentences, where the subjects were memorizing as well as reading.

The findings of most interest were the individual differences in the way that word frequency modulated subjects' gaze durations, particularly when the subjects were reading while maintaining sentence-final words from previously-read sentences. Most of the speed advantage of the high-span subjects came from faster lexical access rather than faster word encoding. This conclusion comes from the regression analysis relating gaze duration to word length and word frequency, for all but the final words in the sentences. The regression analysis produced very similar word length parameters for readers of all spans, but produced smaller word frequency parameters for readers with high spans. Specifically, the word frequency parameter (in msec per log unit of frequency) was 41 msec for the low-span subjects, and 28 msec for the high-span subjects. The word length parameter (in msec per letter) was 47 and 43 for the low and high groups respectively.

These results suggest that better readers read faster, partly because they can do lexical access faster, and they use their extra time for task-specific requirements. In this case, the task specific requirement is maintaining the storage of sentence-final words. The analyses reported below further localize the effect of the load constituted by the sentence-final words on the reading of subsequent sentences.

Even though people with higher spans read faster, they spent more time on the sentence-final words. The mean gaze durations on the sentence-final words is 519 and 715 msec for the low and high-span subjects, respectively.

Reading under load versus no load. While the first sentence of each screen is being read, there are no sentence-final words being stored. Thus the reading characteristics on the first sentence typify a normal no-load situation, in contrast to the reading of subsequent sentences. The interesting result is that the low-span subjects read very similarly under load and under no load, while the high-span subjects adapt to the load condition. In particular, the high-span subjects have a lower lexical access parameter under the load condition. The high-span subjects have a lexical access parameter of 38 (msec per log unit of frequency) on the first sentence on a screen (no load), but 22 on the remaining (load) sentences. The low-span subjects have similar parameters in the two situations (39 for the first sentence only, 48 for all the subsequent sentences). The upper left-hand panel of

Figure 3 shows the decrease in the lexical access parameter for the high-span subjects from the no-load to the load condition. The high and low span subjects differ reliably from each other in their lexical access parameters in the load condition ($F(3,5143)$ = 5.89. p < .01. in a between-groups regression analysis in which the mean gaze durations for the two groups have been equated. and only the word-frequency parameters differ). By contrast. the two groups have similar word-frequency parameters in the no-load condition ($F(3,1400)$ = 1.17. n.s.). The very same pattern of results (relating span to the word frequency parameter in load and no-load conditions of reading) was obtained in another study (described below). in which the sentence-final words constituted a sentence. The replication is shown in the upper right-hand panel of Figure 3.

Figure 3 showing lexical access and word encoding parameters

The effect of reading under load was selective. not just in which group of readers it affected. but also in the locus of the effect. Only the lexical access parameter. and not the word encoding parameter was affected by load. (Recall that the lexical access parameter relates gaze duration to word frequency. while the word encoding parameter relates gaze duration to word length). As the lower panels of Figure 3 show. the word encoding parameter remains approximately unchanged for both high and low-span subjects under load or no load. The process of word encoding may be so automatic that it is not affected by the load imposed by storing a final word from a previous sentence. By contrast. the lexical access process does show the selective effect of load on the high-span subjects.

These results dovetail with the result reported above. that a main difference between the high and the low span readers in the span task is in lexical access. with high-span subjects taking less time for it. During the reading of the first sentence only. a no-load situation. lexical access speed is similar for the high and low-span subjects. Thus the high-span subjects appear to change their reading under a memory load. such that lexical access takes less time. To be more precise. the relation between the word's frequency and its gaze duration is weakened under load. We interpret this result to indicate that high-span subjects activate less of the meaning of a word or activate the meaning to a lesser degree under load. This type of modification to "normal" reading is similar to what we have observed in speed reading. during which the relation between word frequency and gaze duration is weakened even more (see Just & Carpenter. 1987).

Reading when the sentence-final words form a sentence. Because it is generally easier to store and retrieve words that form a sentence. we constructed another form of the span task in which the sentence-final words formed a sentence. The following example illustrates how two sentence-final words form the sentence *Parcels arrived*:

I rushed to the door as the mailman approached and expected to receive several parcels. *A person resembling a poor clergyman or a poor actor* arrived.

The right-hand panels of Figure 3. labeled *Replication 2.* present the data from the sentence condition. In general. this condition replicates the selective effect of memory load on the high-span subjects' lexical access time. and the lack of effect on their word encoding time.

The eye fixation behavior was generally similar in the two tasks. The overall reading rate was approximately the same (the mean gaze durations were 317 in the conventional

Replication 1   Replication 2

LEXICAL ACCESS PARAMETER
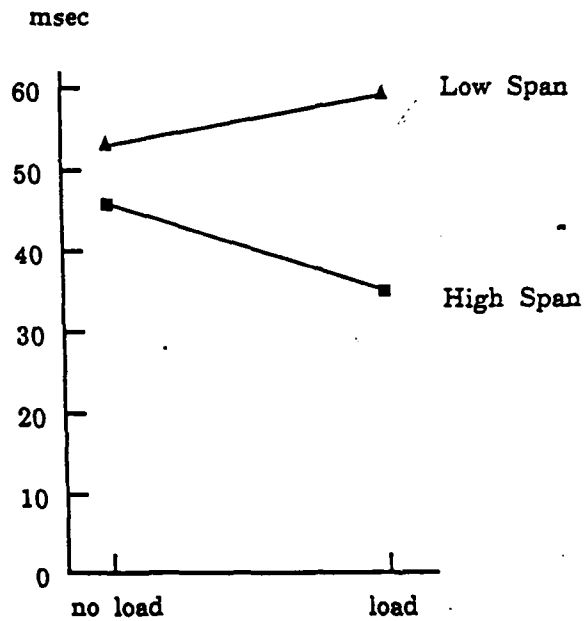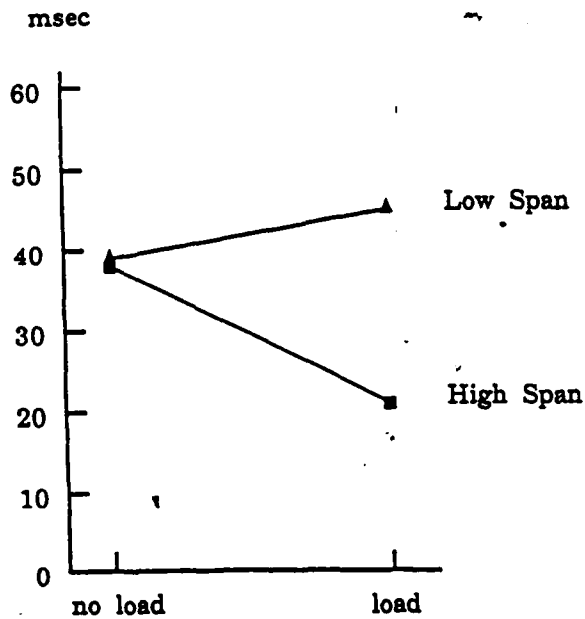
WORD ENCODING PARAMETER
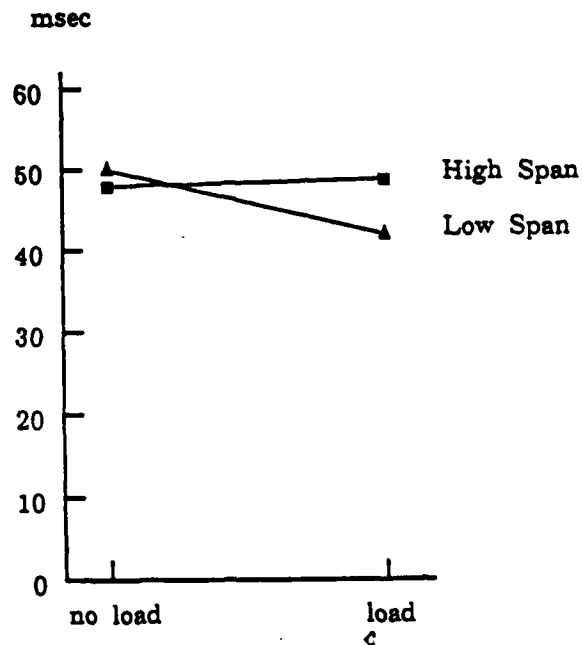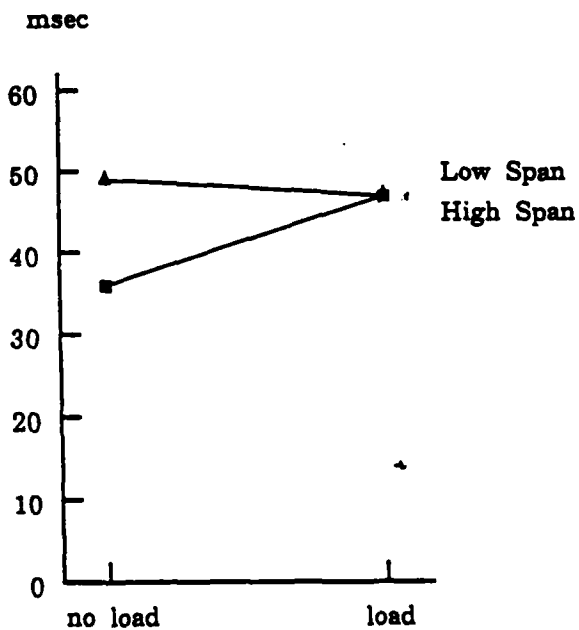
Figure 3. Readers with high spans show a lower lexical access parameter (the top graphs) when reading with a memory load than do readers with low spans. By contrast, the word encoding parameter (the lower graphs) are similar. Replication 1 represents data from the memory span task in which the words were unrelated; replication 2 represents data from the memory span task in which the words formed a sentence.

task. and 344 msec in this new task. exclusive of sentence-final words). The subjects spent slightly less time on the sentence-final word (602 msec versus 565 msec) in the condition in which these words formed a sentence.

In passive memory span tasks. people can recall about seven unrelated words. but about twice as many if the words form a sentence. In this study. however. the mean recall of sentence-final words increased from 2.9 in the conventional reading span task to only 2.5 when the words formed a sentence. This slight increase in recall appears to have been purchased at the expense of a slightly slower reading speed during the reading of the sentences (excluding the time on the sentence-final word). It may be that the construction of the sentence formed by the sentence-final words (particularly the binding of the words to the syntactic structure) competes for some of the same resources as the parsing of the sentence that is being read.

The main result of this study is that the presence of a memory load affects only the lexical access process. not word encoding. and only for the high-span readers. not for low-span. This result reveals some of the detail of the trade-off between comprehension and storage when storage demand is manipulated. and pinpoints the flexibility of the better readers.

The trade-off between storage and difficult comprehension

Sentences can vary in many respects that affect how difficult they are to comprehend. and this variation should affect the consumption of working memory resources. Within the collection of stimulus sentences that are used in administering the reading span test. some sentences intuitively seem harder than others. because of a mixture of factors including vocabulary. syntax. the abstractness of the topic. and so on. Consistent with intuition. the reading speeds on the harder-looking sentences are generally slower than on easier-looking sentences (differing by a factor of almost two at the extremes of the distribution). Furthermore. the recall of sentence-final words on those sets of sentences that contain a particularly difficult sentence is often lower than on other sets. These informal observations relating judged sentence difficulty to reading speed and recall of sentence-final words support the view that more difficult sentences consume more processing resources. and hence leave fewer resources available for storage of sentence-final words.

In the experiment described below. we studied the trade-off between language processing and storage by systematically varying the number of difficult sentences in a set. and examining the resulting effect on the recall of sentence-final words. Because the previous experiment indicated that lexical access was a source of individual differences in reading comprehension. the words used in the difficult sentences were less frequent and less concrete. An example of an easy sentence was:

I thought the gift would be a nice surprise. but he thought it was very strange.
By contrast. an example of a difficult sentence was:
The incorrigible child was reprimanded for his apathetic behavior toward the elders.

The kind of working memory we have proposed and installed in the READER model is of the blackboard variety. meaning that it is a site of interaction for processes from several levels -- lexical. syntactic. semantic. and so on. Consequently. difficulties in comprehension at any level should manifest themselves in decreased storage capacity. In particular. we predicted that the comprehension of a difficult sentence in the reading span

task should interfere with the ability to maintain the storage of sentence-final words from the preceding sentences in the set. The recall of sentence-final words should decrease as the number of difficult sentences in the set increases. However, these trade-offs are expected only when there is a competition for resources. that is. if the reader is operating at the limit of his working memory capacity. For example. the presence of difficult sentences should be particularly damaging to a subject with a span of two when he is processing a set of three sentences. By contrast. difficult sentences should have no effect on a subject with a span of four when he is processing a set of two sentences.

The easy and hard stimulus sentences were combined into four different types of sets. varying in the number and location of difficult sentences that they contained. Some sets were composed exclusively of easy sentences and some exclusively of difficult sentences. There were also two intermediate conditions that contained only one difficult sentence. either in the second or in the last serial position of the set. The sentences were presented one at a time on a CRT. The subject controlled both when the sentence was initially presented and when it disappeared by pressing a button. thus providing a measure of the time taken to read each sentence.

Unlike previous studies. in which the criterion for measuring reading span entailed the comprehension of an uncontrolled mixture of hard and easy sentences. this study required a measure that took sentence difficulty into account. Each subject's span was defined here as the largest set of easy sentences for which he always recalled at least 80% of the sentence-final words. This criterion produced distributions of spans similar to those in earlier studies. After categorizing the subjects into high. medium. and low spans. we then examined their recall in sets of different sizes containing different numbers of difficult sentences.

The results confirmed that reading a difficult sentence did interfere with the ability to recall the sentence-final words of the set of sentences. involving the predicted interactions with individuals' span and the number of sentences in a set. Consider first the high-span subjects. particularly their recall of sets of four sentences. as shown in Figure 4. In this situation. they are operating at the limit of their span. Their recall is best with sets that have no difficult sentences. and slightly impaired if a set of 4 sentences contains a difficult one among them. Their recall is substantially poorer if all 4 sentences in a set are difficult. In this case. their recall decreases to the level of set size 3. The increased processing burden imposed by the difficult sentences draws resources away from the task of retaining the set of sentence-final words. Although the high-span subjects are affected by the presence of difficult sentences in sets that push them to the limit of their span. they show no effect of sentence difficulty for sets below their span. producing a reliable interaction between the set size and the number of difficult sentences $(F(4.32) = 6.55. p < .01)$. In situations in which they have working memory capacity to spare. they use it to perform the additional processing without any consequence to their storage of sentence-final words.

Insert Figure 4 of recall of hi. med. and lo span subjects

Medium span subjects show interference effects for sets of length three and four. which are at or above their working memory capacity. Their recall performance is poorer for sets composed of difficult sentences than sets composed of easier sentences. As with the high-span subjects. medium span subjects show no interference effects for sets that are below their span. in this case. for sets of length two. producing a reliable interaction
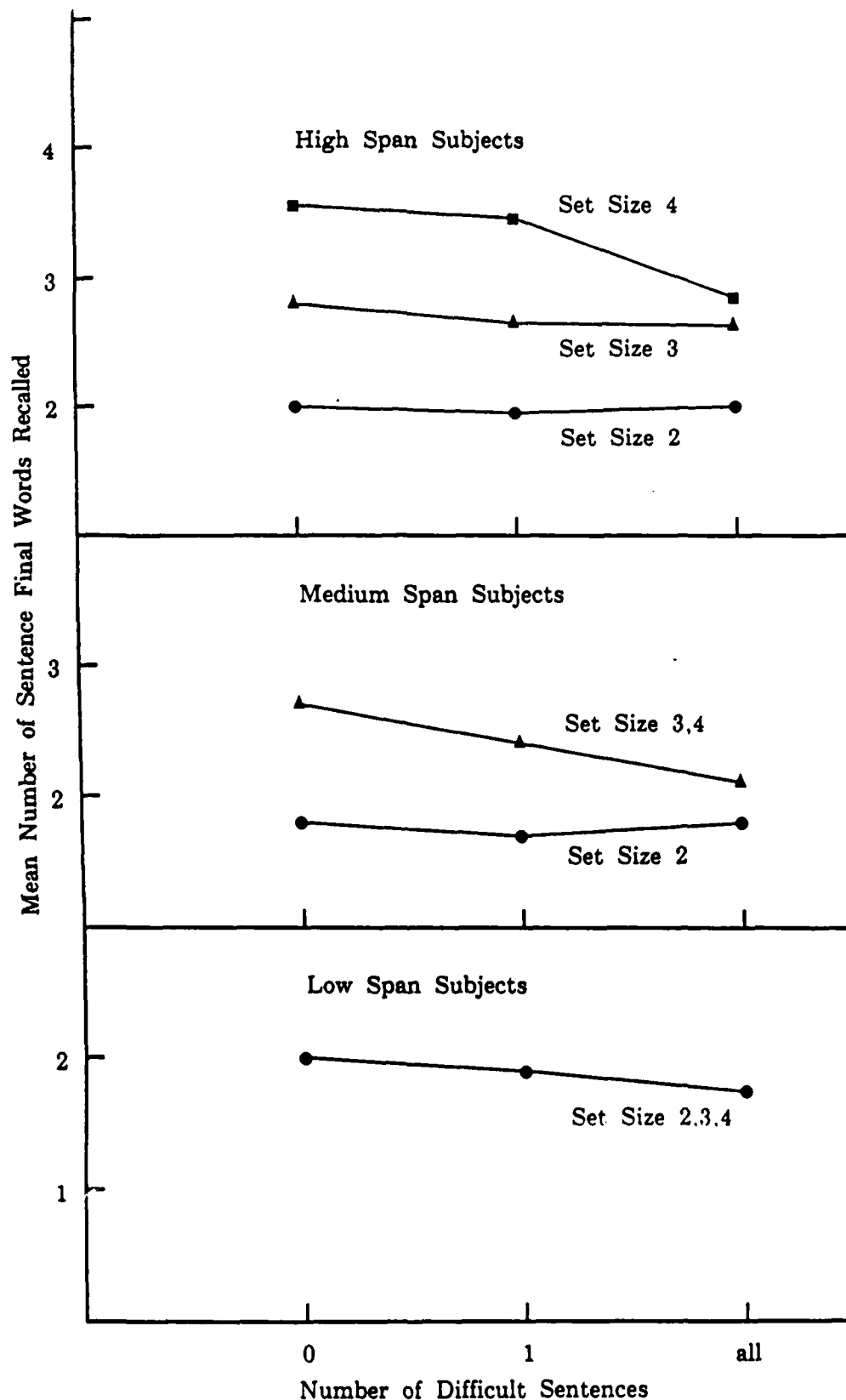
Figure 4. Readers show interference if the span contains difficult sentences for set sizes that are at or above their span. The graph shows the number of words recalled when there was 0, 1 or all difficult sentences in the set. The high span subjects (the top graph) show interference with set size 4: the medium span subjects (the middle graph) show interference with set sizes 3 and 4: and the low span subjects (the lower graph) show interference with all set sizes.

between the set size and the number of difficult sentences ($F(3.33) = 5.68$. $p < .01$).
When they are operating below the limit of their span. the recall is the same irrespective
of whether the sentences are all easy. have one difficult sentence. or are all difficult.

Finally. the low-span subjects show interference for sets of any length. because set
sizes of 2. 3. or 4 are all either at or above their capacity. However. the effect is only
marginally significant. ($F(3.21) = 2.36$). perhaps because of a floor effect.

Thus. the experiment shows how language comprehension can interfere with storage.
in a way that would be difficult to explain without the working memory theory. It also
demonstrates the clear differences among individuals and how the interference effects occur
only when subjects are operating with sets that are at or above their working memory
span.

Implications from the span task

Performance in the reading span task reflects the trade-off between computation and
information maintenance in working memory. as well providing a measure of differences
among individuals in their working memory capacity for language comprehension. The recent
experiments provide a detailed account of the trade-off. indicating that it affects the
different levels of comprehension selectively. The process of lexical access. the activation of
a word's meaning. entered into the trade-off for high-span subjects who were reading under
a memory load condition. By contrast. the process of encoding a word. recognizing the
visual pattern it forms. did not enter into the trade-off. and always proceeded the same
way. regardless of memory load.

The processing burden imposed by a difficult sentence manifests itself only if a
subject is close to or above his span: otherwise. he has no need to trade away maintenance
capacity to provide the additional computational resources required by a difficult sentence.
Thus the effect of a difficult sentence is different for different readers. and is different for
different memory load conditions.

The computations required to perform a complex but practiced task like language
comprehension can be executed in the presence of other forms of thought. provided that
both tasks together do not exceed the capacity of working memory. When competition for
working memory resources arises during language comprehension. more automatic
comprehension processes appear to continue to execute without modification. while slightly
higher level processes are modified to produce faster execution.

Syntactic analysis and working memory

The reason that human language must have syntax is that a speaker can produce
only one word at a time. so that an utterance must consist of a sequence of words.
Syntactic organization allows us to build non-sequential grammatical structures out of a
sequence of words. Even though an utterance must have a linear sequential structure. the
underlying concepts are not linearly related to each other. nor are the grammatical relations
among the words strictly between adjacent words. Syntactic organization allows a sequence
of words to coalesce to form higher order constituents (phrases and clauses) that can bear a
variety of grammatical relations to each other. The syntactic organization provides part of

the temporary structure to organize the words until the underlying concepts are understood. The coalescence occurs in working memory. where the cumulating transient structure is held.

Syntactic processes help structure information so it can be held in working memory until the succeeding parts of the sentence are processed and while other non-syntactic processes are executed. If a series of words is unstructured. readers have difficulty recalling even a small number of words that they have read at a normal rate. Typically. a reader can recall no more than six or seven unrelated words in order. Of course. a reader can understand and recall sentences that are much longer than seven words because a sentence has an internal syntactic and semantic structure that helps circumvent this severe working memory limitation. To measure the improvement in recall more precisely. we ran a simple experiment in which we asked subjects to read a single sentence aloud at a normal rate. and then immediately recall it (without access to the written version). The 18 stimulus sentences ranged in length from 8 to 22 words and in number of clauses from one to three.

The mean number of words recalled as a function of the number of words in the sentence is shown in Figure 5. For sentences up to 20 words long. people recall a constant percentage of words (approximately 77%). with a lower percentage for 22-word sentences. The relatively constant proportion reflects the apparently paradoxical result that people can recall about 15 words of a 20-word sentence. but only about 8 words of a 10-word sentence. Of course. they spend approximately twice as much time reading the 20-word sentence. which accounts for some of the increased recall with sentence length.

The ability to recall a much larger number of words from a sentence than from a sequence of unrelated words suggests that the syntactic structure of a sentence provides a structure to which the words of a sentence can be bound during comprehension. This same structure can later provide a retrieval path at the time of recall. Thus the limitation in working memory applies particularly to information that cannot be interpreted. that is. cannot be bound to existing knowledge structures. So long as the binding that is the essence of normal comprehension occurs. about 77% of the words are stored well enough to be recalled. We do not know why the proportion of words recalled decreases at 22-word sentences. but it may be that the ends of sentences of such length are not being completely comprehended in the first place. It is plausible that the storage of the early part of such a long sentence consumes some of the resources necessary for the comprehension of the very late part.

Ericsson and Staszewski (this volume: Ericsson. Chase & Faloon. 1980) have demonstrated the mnemonic power of binding isolated elements to a familiar structure. One of the most dramatic demonstrations of this power is the ability of college students to increase their recall for unrelated digits from seven digits to almost 80 or 100 digits. These students. who happened to be runners. became skilled at relating sets of three and four digits to numbers that were already familiar. in their case. running times: then the running times would be linked to a hierarchical structure that enabled them to retrieve the items in the correct order. Memorizing a sequence of digits this way shares some properties of language comprehension. namely the circumvention of working memory limitations by on-line binding of successive elements to a hierarchical knowledge structure. Of course. there also are some very important differences between the digit task and sentence comprehension. In the digit task. the knowledge structure to which the digits are bound is fairly inflexible and typically known beforehand. By contrast. in sentence comprehension. the semantic and syntactic structures vary enormously from sentence to

sentence. and they must be determined largely on the basis of the content of the input sequence of words. There is much more to comprehension than storage and retrieval.

The recall of words from single sentences also revealed small but systematic individual differences. The mean number of words recalled increased from low. to medium to high-span subjects. with means of 11. 11.9. and 12.1. respectively. Thus. individual differences are found even if the recall is not in competition with comprehension. and even when the individual words form a meaningful sentence.

FIGURE 5 ----------results of recall of single sentences

The working memory load imposed by syntactic processing

In this section. we consider not only how the presence of a syntactic structure can facilitate the storage of a sentence. but also how syntactic computations compete with the storage functions. In general. much of syntactic analysis in good readers appears to proceed without difficulty. Readers are seldom aware of syntactic difficulties during their processing of a well-written text. However. the processing of certain unusual syntactic structures can tax working memory in a way that illuminates the trade-off between syntactic processing and working memory storage in individuals of varying working memory capacity.

One syntactic structure that has been studied extensively because of its unusual difficulty is a sentence with a center-embedded clause. such as the following:

The salesman that the doctor met departed.

Subjects who listen to sentences with a single center-embedded clause make errors in paraphrasing them about 15% of the time (Larkin & Burns. 1977). Errors rise to 58% (almost random pairing of nouns and verbs) if the sentence contains a double center-embedding. such as:

The salesman that the doctor that the nurse despised met departed.

Center-embedded sentences have been extensively studied precisely because they are one of the few structures that are genuinely difficult for a skilled adult to understand.

Several factors make center-embedded sentences difficult. First. the constituents of the outer clause (*the salesman* and *departed*) are interrupted by the embedded clause (*the doctor met*). so the reader must keep track of the initial noun phrase while he processes the embedded clause. The second factor is that *salesman* plays two different grammatical roles in the two clauses. *Salesman* is the grammatical subject of the main clause but the grammatical object of the embedded clause. Associating a single concept with two different syntactic roles *simultaneously* seems to be a source of difficulty (Bever. 1968). The difficulty does appear to be syntactic because the sentence is easier to comprehend if its structure is changed so that *salesman* is the grammatical subject of both clauses:

The salesman that was met by the doctor departed.
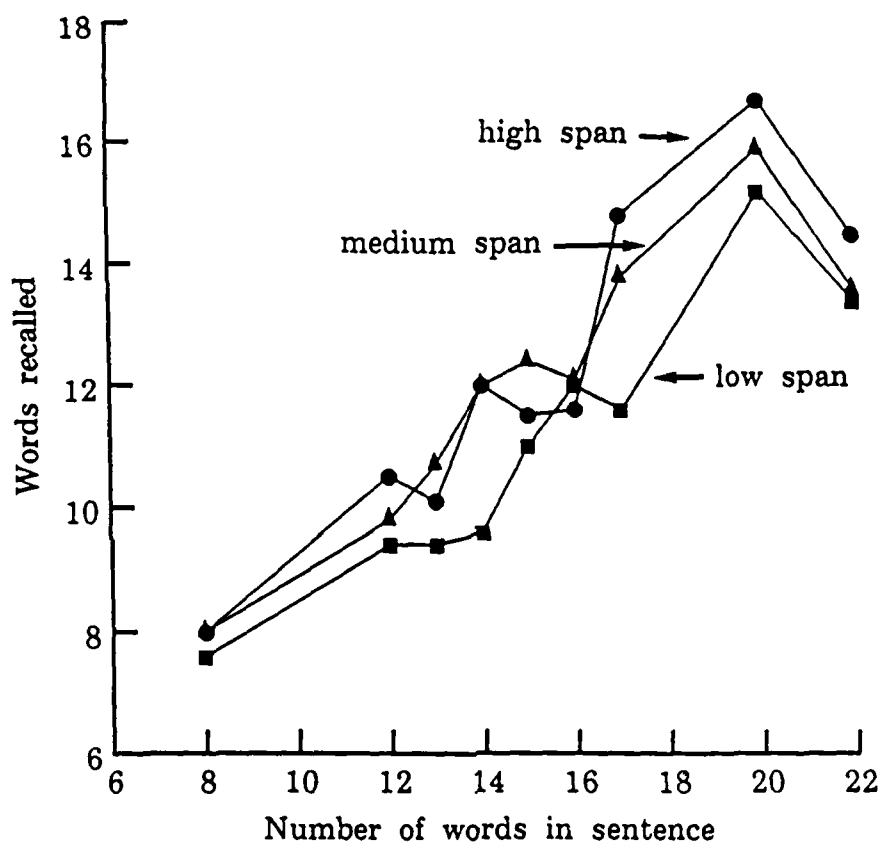
Figure 5. Subjects are able to recall a large number of words that form a syntactically and semantically acceptable sentence. The graph shows the average number of words recalled as a function of the number of words in a sentence from 8 to 22 words. for subjects who tested as having low. medium. and high spans in the reading span task.

One way to determine the nature of the processing difficulty is to compare the word-by-word processing time on center-embedded sentences with other types of sentences that share some of the same properties. For example. consider the two sentences below. the first of which contains a center-embedded clause. while the second contains a right-embedded clause:

Center embedded: The paper that the senator *attacked admitted the* error.

Right embedded: The paper that *attacked* the senator *admitted the* error.

In both sentence types. the embedded clause intervenes between the main subject and the main verb. However. in the right-embedding case. the main subject is also the subject of the relative clause. while it is the object of the relative clause in the case of the center-embedding. The sentences with center-embedding take longer to process. with the extra time being expended during the reading of the two verbs (Ford. 1983). The difficulty is probably attributable to the pairing up of the verbs and nouns that play different grammatical roles. The subject-verb pair of the outer clause is the same in both cases (*paper admitted*). But the process of putting this pair together is more difficult if *paper* has been playing the role of a grammatical object of the embedded clause in the meantime. The sheer memory load of retaining the first noun is not the problem. We know this because the word-by-word processing times increase only at the end of the embedded clause. Also. retention of the first noun is necessary in both center-embedded and right-embedded sentences. so that retention can't be the distinguishing problem. Thus. all the evidence points to the pairing process concurrently with the maintenance of the dual syntactic roles as the source of the difficulty.

In a more detailed examination of the parsing in these constructions. Jonathan King. a graduate student working in our laboratory. found that the difficulty is most severe for subjects with low working memory spans. and that such subjects are particularly susceptible to interference from a concurrent memory load. The syntactic processing load imposed by center-embedded sentences was examined by pitting it against a memory load of 0. 3. or 5 digits that subjects were asked to store while they read the sentence. The sentences were read one word at a time in a self-paced "moving window" paradigm (Just. Carpenter. & Woolley. 1982). such that the subject had to press a button to enable the presentation of each succeeding word of a sentence. Only one word is displayed at a time. and the elapsed time during a word's display before the next button press indicates the subject's processing time on that word.

The readers with high spans tended to read faster and have less difficulty with center-embedding than those who were classified as having medium spans or low spans. Figure 6 shows the time spent on reading each word of the center embedded sentences in trials in which there were no extraneous digits to be stored during the reading. The high-span subjects had relatively little difficulty with the center-embedded sentences (or with right-embedded sentences. either). The medium and low-span subjects. in contrast. took longer and showed noticeable elevations in reading times in the area that introduced the most complex syntactic computation.

FIGURE 6 -high. med. low-span subjects. all at zero load

The reading times on the center-embedded sentences were elevated particularly if the
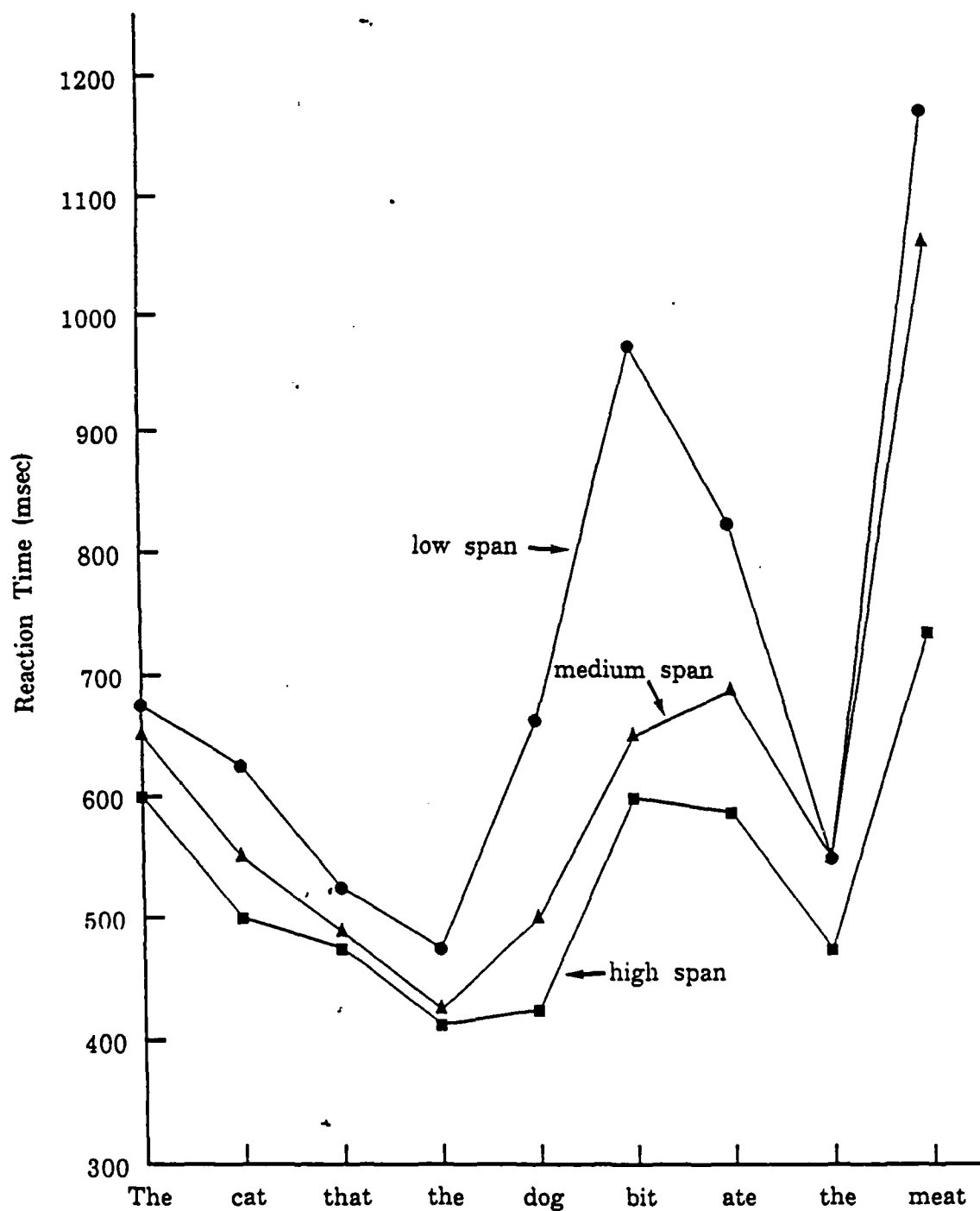
Figure 6. The reading time for each word in a center embedded clause tends to peak at the verbs (as well as at the end of the sentence). indicating that this is the locus of syntactic difficulty. The graph shows the reading times when subjects were processing the sentences without any extraneous memory load. The three graphs are for subjects who had tested as having high. medium. and low spans in the reading span task. Low span subjects have the longest reading time overall and show particular difficulty on the verbs.

subjects were storing extraneous digits and if they were medium-span or low-span subjects. Moreover. the elevation occurred primarily on the critical verb. Figure 7 shows the results for the medium span subjects. who present the clearest test of the proposal that storage resources compete with syntactic parsing resources. because the center-embedded sentences seem to lie at the limit of these subjects' normal processing capability. That is. the medium-span subjects have little difficulty processing the center-embedded sentences in the absence of an extraneous load. and their performance deteriorates as the extraneous load is increased. By contrast. the low-span subjects have difficulty with the center-embedded sentences even in the absence of an extraneous load. while the high-span subjects have little difficulty even in the presence of an extraneous load.

The variation in memory load makes its major impact on reading time when the reader encounters the first verb. the first point in the sentence that requires the difficult syntactic computations. as predicted by the immediacy of interpretation. In the sample sentence used in Figure 7. the first verb is *bit*. The results also support the hypothesis that working memory resources are shared by many different kinds of processes. In this case. maintenance of the digit load shares resources with the syntactic assignment process. Moreover. the graded nature of the effect. from digit loads of 0 to 3 to 5. indicates some degree of continuity of the sharing.

FIGURE 7 ---------- med span subjects. at all loads

This study demonstrates for the first time that comprehension ability is closely related to the ability to perform syntactic computations. and it links this ability to storage and processing resources in working memory.

The nature of working memory

In this section. we will describe what the computational approach tells us about the nature and capacity of working memory. Our claim is that this approach provides a different perspective on the nature of working memory than the older view that it is a passive buffer. with a capacity of seven chunks. whose primary role is information maintenance during learning.

Working memory as a computational arena. A major implication of the computational approach is that resources are shared among different component processes in performing a complex task. and that there are lawful trading relations among some of the processes that compete for resources. In particular. we have shown that lexical access and syntactic analysis are two of the comprehension processes whose resource needs can be traded away against the storage of information in working memory. Symbol manipulation competes with symbol storage when capacity limitations are reached.

One of the important results is that there are systematic differences among individuals in their working memory capacity for a given task. The trading relation come into play most clearly when readers' working memory was being taxed to capacity. Moreover. readers of different working memory capacities begin to be taxed at different loads. The presence of difficult sentences in the reading span task affected the recall of sentence-final words only if the number of sentences in the set equaled or exceeded the
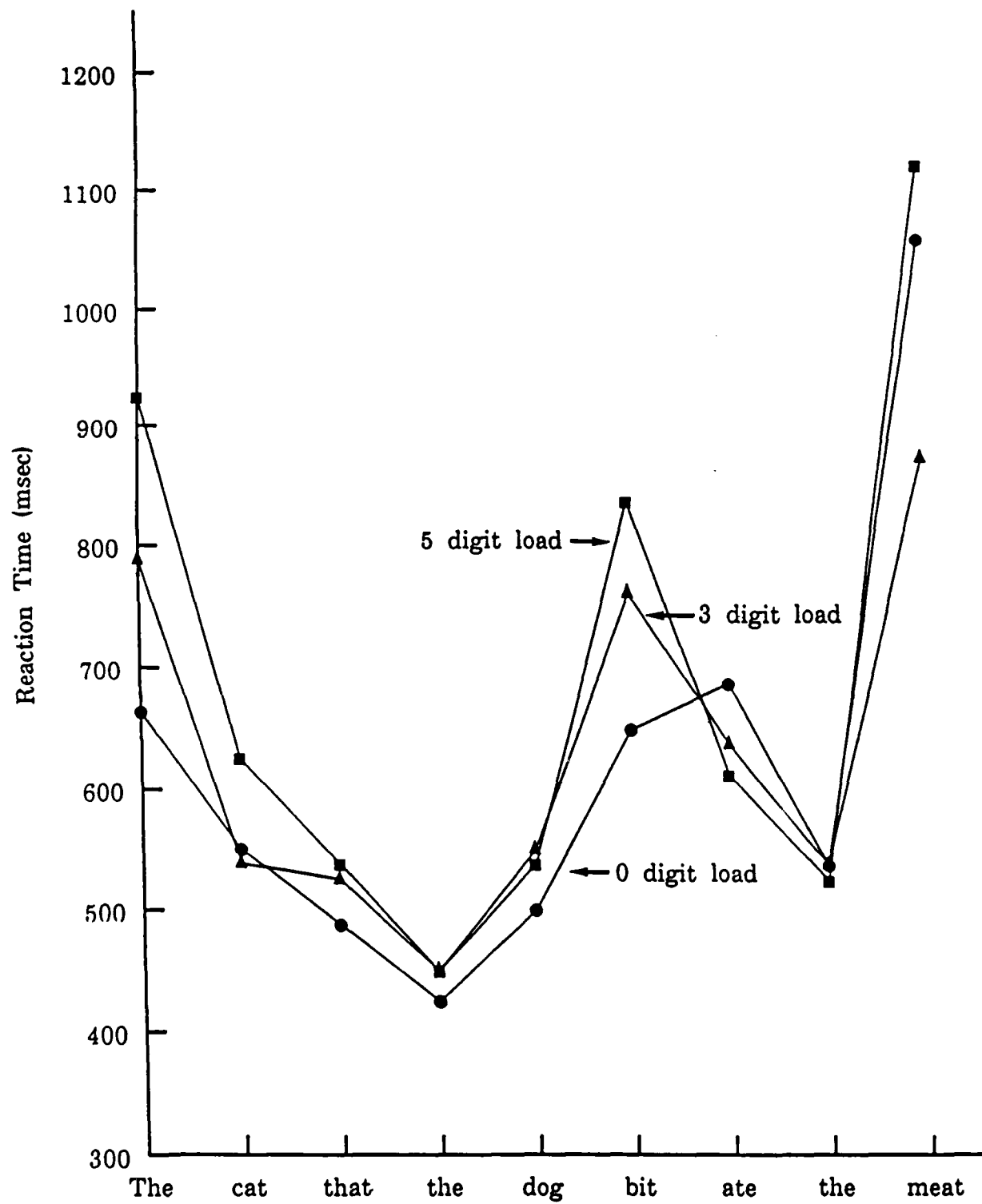
Figure 7. The reading time for each word in a center embedded sentence for medium span subjects with three memory loads: 0. 3. and 5 digits. The effect of the memory load is particularly apparent at the location of the verb.

subject's reading span. The experiments show that the trading function is different among individuals in at least two ways. The main result is that some subjects have a smaller pool within which to trade in this task. In other words, their working memory capacity is small in the reading span task. The second result is that high span subjects dynamically reallocate their resources in a task when an additional new demand is imposed. This result suggests the possibility that individual differences in working memory capacity may be due in part to individual differences in the effectiveness with which working memory resources are allocated. If this hypothesis is correct, it may be possible to modify working memory capacity in some cases by telling subjects what allocation policy to use.

The trading functions are the manifestations of mental resource allocation policies, which indicate the resource pool within which the trades are made and the conditions under which resource allocations are changed. One small example of a resource allocation policy is the shift of resources away from lexical access among the high-span readers when sentence-final words have to be maintained in working memory. In this perspective, the trading functions indicate how people allocate their ability to think about more than one thing at a time. The competing "things" can be different component processes of a single complex task, or components of two different tasks.

Our new findings extend previous demonstrations of the effects of competition between processing and maintenance in working memory (Baddeley & Hitch, 1974; Baddeley, 1986; Case, 1985). Many of the Baddeley and Hitch studies have shown that when memory load increases above some threshold, there are performance decrements on a concurrent task, such as the time to judge sentences as true or false. The current studies progress further by specifying the precise characteristics of the trading relation, that is, which language processes are traded off and which are not, the conditions under which the trade-off occurs, and examining those processes that are sources of individual differences. These results tell us both about the nature of comprehension and about the nature of working memory.

Readability and working memory. The experiments also provide a new perspective on text readability. The first atheoretical characterizations of text difficulty, such as the Flesch (1948) scale, attempted to predict readability in terms of a text's structural properties, such as the familiarity of the words and the lengths of the sentences. However, even if they have some predictive validity, such scales provide little insight into the psychological processes that are involved. The new perspective on readability gained from our considerations of working memory is that readability is not just a function of the difficulty of a given portion of text, but is also a function of how that difficulty impinges on the maintenance of other information. In other words, a difficult sentence can make a reader forget what he had previously read. In this perspective, an inherently difficult sentence should be more damaging to the comprehension of a text if it occurs at a time when the reader is storing lots of unfinished business (partial products).

Another recent insight is that anaphoric reference to a proposition that is no longer in an activated state in working memory decreases readability (Kintsch & Vipond, 1979). Kintsch and Vipond correctly predicted that a text that frequently referred to distantly-mentioned topics would be more difficult to read. These two new considerations of the computational and storage requirements of comprehension help make readability a theoretically-based measure of operational load rather than an inherent property of a text.

Measuring working memory capacity. Each of our reported experiments demonstrates that we can measure the relative working memory capacities of different subjects in a given domain. In this approach, working memory is measured in terms of operational capacity.

rather than in terms of chunks of static storage. Working memory capacity cannot be viewed as some general property of a fixed structure. Moreover, the operational approach suggests that there is no absolute measure of working memory capacity; it can be measured only with respect to a set of mental operations in a given domain. In this view, it would not be surprising if working memory capacity measured in one task was not predictive of performance in a different kind of task. Working memory capacity will be specific to a particular person as well as specific to the processes in a particular domain.

Characterizing the resources of working memory in terms of operational capacity provides a new view of the benefits of chunking as it occurs during comprehension. It is well-known that if information has been organized into chunks, memory performance improves, decreasing the working memory resources that are required for storage. But what about the use of the resources that perform the chunking? Chunking is not cost-free. The act of constructing a new chunk is time-consuming (Simon, 1974). The act of language comprehension can be viewed as recoding (chunking) an input string of symbols into an organized structure. If the chunking is particularly difficult, as is the case in the comprehension of center-embedded sentences, then it can create a competition for limited working memory resources. We described how the comprehension of center-embedded sentences imposes a transient processing load at the point of a key syntactic computation (binding each of the noun-verb pairs that constitute a syntactic chunk). This result shows that chunking falls within the trading relation between working memory storage and processing when the reader is performing at capacity. Chunking is an effective means to pack information into working memory, but it is effective only if there are working memory resources available to do the packing. Working memory capacity must be measured in terms of both chunks and the resources that are used to do the chunking.

The computational framework also highlights the fact that any complex task like language comprehension requires multiple levels of representation. Like READER, a human comprehender who encounters a given word of a text must have representations of letters, morphemes, the word pattern itself, the word-concept, the phrase and/or clause to which the word belongs, and a representation of the referential world. How can the multiplicity of levels be made congruent with the apparent limitation in capacity? The suggested resolution is that the limitation is specific to a particular level of representation. A person may only be able to hold a limited number of items at a particular level, but symbols from several levels can be stored simultaneously. This formulation is reminiscent of Miller's (1956) observations concerning the ability to make absolute judgments about a perceptual stimulus; as the number of varying dimensions of the stimuli increases, so does the performance, measured in information theoretic terms. To perform a complex task like language comprehension, the mind has evolved multiple overlapping and partially redundant levels of representation, increasing the total processing capacity.

Levels of processing and their time course

The computational framework also provides a different perspective on the time course of different types of information in working memory. The time course of a given part of a representation may be determined by the computations that are being operating on it. The partial and final products of thought may persist only as long as they are being acted upon. Information that serves only as the input into an early computation may decay after serving its purpose.

The different types of information used in language comprehension, such as letter

level. word level. or syntactic level. have different temporal profiles. They can differ in the time when they begin to become activated. when they actually reach the threshold state of activation. and how long they remain in the activated state. Not all levels have to be co-temporaneously activated. The distinctive temporal profiles of the different levels means that they have different lifespans in working memory.

The main purpose of some of the earlier levels of representation is to enable a later level to operate (e.g.. the letter level enables the word-percept). In at least two of the lower levels (word-percept. letter typecase). the evidence suggests that the representation is very brief. or if persists. it does so at a low activation level. By contrast. memory for the higher-levels. such as the gist (the referential level). is long lasting.

The perceptual level. The brevity of the representation of the typecase of a text has recently been demonstrated in an experiment that surreptitiously changed the case during a saccade that separated two successive fixations (McConkie and Zola. 1979). The type case of a given word was sometimes changed while a reader made a saccade to see if he "remembered" it from one eye fixation to another. At all times the words of the text were composed of letters of alternating case (each letter was in a different case from the preceding letter). However. between some fixations. while the reader's eyes were in motion. the case of all the letters was changed from one state to the other. Each line of the example below shows how one line of the display looked during a given fixation. whose location and sequence number is indicated by the digits above the fixated text.

```
              1
        In ThE eStUaRiEs Of ThE fLoRiDa EvErGlAdEs ThE rEd MaNgRoVe
(case
change)                      2
        iN tHe EsTuArIeS oF tHe FlOrIdA eVeRgLaDeS tHe ReD mAnGrOvE


                             3
        iN tHe EsTuArIeS oF tHe FlOrIdA eVeRgLaDeS tHe ReD mAnGrOvE
(case
change)                                    4
        In ThE eStUaRiEs Of ThE fLoRiDa EvErGlAdEs ThE rEd MaNgRoVe
```

Changing the typecase of the letters between fixations produced no effect on the eye fixation behavior of a reader. neither on fixations nor on saccades. In fact. the display changes were not even visible nor detected. The lack of interference suggests that there is little memory for typecase from one fixation to the next. Once the word encoding processes have done their work. no other processes operate on the typecase information. hence it no longer needs to be maintained in working memory.

The lexical level. The lexical level. namely the representation of the word meanings activated by the visual or auditory percept of a word. has a longer lifespan. Many word-percepts are associated with more than one word meaning: their relative lifespans are *particularly distinguishable in the case of a homonymous word like bank.* The word-percept activates both the intended and unintended meanings of *bank.* The unintended meanings of a word have a lifespan on the order of 300 msec. This result has been obtained in cross-modality priming experiments (Seidenberg. Tanenhaus. Leiman. & Bienkowski. 1982: Swinney 1979). For example. during the comprehension of a sentence like *George went to withdraw some money from the bank last week.* the unintended meaning of *bank.* pertaining to the

side of a river bed. is briefly activated. This lifespan of the unintended meaning provides a rough estimate of lexical activation that is not supported by other levels of processing. The unintended meaning does not enter into other levels of processing. and hence its representation is not maintained. By contrast. the intended meaning of a word remains activated for at least a second after the word has been encountered. The word meaning that receives collaborative activation from other sources becomes the selected interpretation of an ambiguous word. The main purpose of activating a word meaning during language comprehension is to enable higher level processes such as syntactic. semantic and referential operations. The higher level processes can prolong the life of a lower-level trace that would otherwise decay much sooner.

The syntactic level. A seldom-cited point in a well-known article provides a useful insight into the time course of certain syntactic information (Jarvella. 1971). Jarvella's experiment examined how verbatim memory decays after a sentence boundary. by contrasting the recall of a target clause (e.g..*after he had returned to Manhattan*) when it was either part of the second-to-last sentence in a text (Condition A) or part of the last sentence (Condition B).

CONDITION A. Taylor did not reach a decision until *after he had returned to Manhattan.* He explained the offer to his wife.

CONDITION B. With this possibility. Taylor left the capital. *After he had returned to Manhattan.* he explained the offer to his wife.

As the subjects were processing the text. they were interrupted at the end of the second sentence. just after having been presented the word *wife.* and were asked to recall as much of the preceding text as they could. Recall of the last-processed clause (*he explained the offer to his wife*) was similarly high in Conditions A and B. The important data concern the recall of the critical clause (*after he had returned to Manhattan*) that preceded the last-processed clause. Recall of this clause was much poorer when it was part of the preceding sentence (Condition A) than when it was part of the last sentence (Condition B). Moreover. recall dropped off abruptly at the sentence boundary. rather than gradually decreasing with the distance from the end of the sentence. providing evidence of the sharp decay of verbatim information at clause boundaries.

A seldom-cited aspect of Jarvella's study suggests that what drops off abruptly at clause boundaries is not just the knowledge of the words. but the knowledge of the word-order. In order to measure the recall of word order. Jarvella used a second. more strict scoring method that gave credit for recall of a word only if all the subsequent words were recalled in the correct order. Figure 8 contrasts the two scoring methods for Condition B. in which the critical clause was part of the last sentence. This strict scoring method shows that word order information from a previous clause drops off very sharply at the clause boundary. By contrast. the first. looser scoring method described above shows that memory for the words themselves does not drop off as much at clause boundaries. The difference indicates that people have poor memory for the exact order of words in the preceding clause. Word order is a very important cue to syntactic analysis. and it may be that once the syntactic analysis has been done on a clause. the word order information is no longer retained. By contrast. while a clause is being processed. syntactic and semantic processes that relate the later words to earlier words help keep the precise words active. along with information that preserves word order.

Insert Figure 8 -- Jarvella's two scoring schemes

There are several reasons why the exact wording of a preceding sentence or clause might be forgotten. One possibility is that after the syntactic analysis at the end of a clause has been performed. there may generally be little further need for retaining the exact wording information. and it may be intentionally purged. Another related possibility is that the syntactic computations that occur at the end of a major syntactic constituent are so demanding of resources that the exact wording information is displaced by the computations. Eye fixation studies consistently find an extra amount of time spent on the last word of a difficult sentence. and sometimes on the last word of a non-final clause (Just & Carpenter. 1980). We have attributed this extra time to "wrap-up" processing. tying up loose ends that have been unresolved until the end of the sentence. Some but not all of these loose ends are probably syntactic. The combined load of the leftover computations from several levels may cause forgetting of the exact wording information pertaining to syntax because of the computation-storage trade-off that we have described.

In this section. we have described how different types of information that are developed during the process of comprehension have different time courses in working memory. The time course of information in working memory may be a function of its participation in various component operations of comprehension. Thus. earlier levels of information (such as typecase) that do not directly contribute to the higher-levels of semantic and referential interpretation have a short lifespan. Similarly. the unselected meanings of ambiguous words persist for a relatively brief duration compared to the selected meanings of ambiguous words. because the latter meanings are acted upon by other productions involved in constructing the meaning of the text.

The idea that working memory serves as the arena for computations that occur in the service of language processing provides a different perspective on the purpose. nature. and time course of representations. It becomes clear that the feast that William James described is an inherent part of any complex cognitive task and that working memory can be best understood when it is analyzed in the context of its role in such tasks.

A final note

The approach to language comprehension taken in this chapter is to treat it as another part of the symbol manipulation that constitutes thought. rather than as a separate system. In most respects. the language processing we have described operates within the type of general cognitive architecture outlined by Herbert Simon and Allen Newell. To be sure. language processing has some distinctive characteristics. as does spatial processing or numerical processing. But they all function within a shared cognitive architecture. operating in coordination with each other. In many respects. language comprehension seems to provide a prototype rather than an exception to the way human thought relies on working memory. Language and working memory may have evolved together in the service of meaning transmission. and by so doing. may have provided some of central resources of human thought.
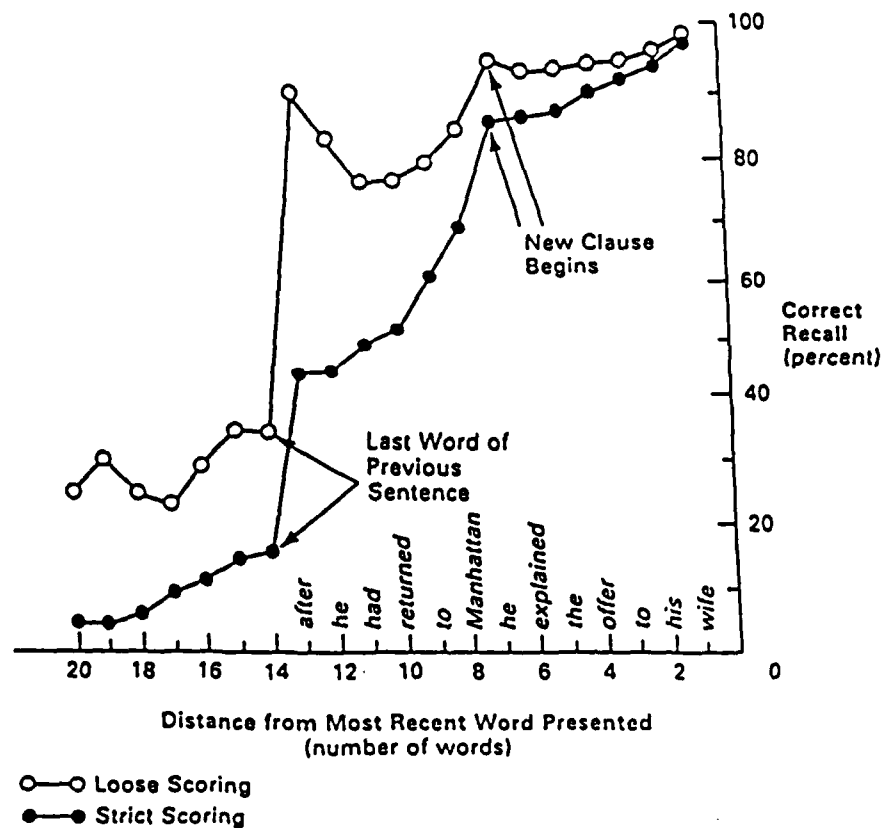
Figure 8. The contrast between two scoring methods by Jarvella (1971) suggest that memory for word order is responsible for some of the drastic decline at a sentence boundary. The graph contrasts the loose scoring criteria (open circles) in which any correct recall was credited with the strict scoring criteria (closed circles) in which words were only credited if subsequent words were in the correct order. Source: Adapted from Jarvella. 1971. Figure 1. p. 411. Used with permission of Academic Press and the author.

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